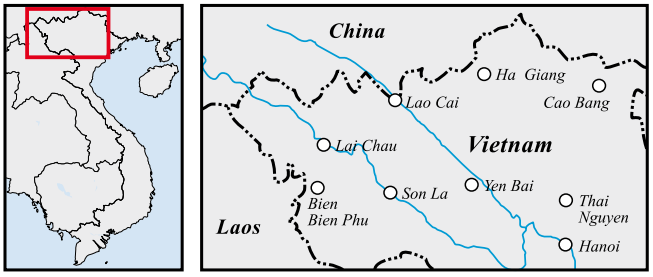
Young faults in northern Vietnam: a case study of the Red River Fault Zone

Młode uskoki w północnym Wietnamie: przykład ze strefy uskoku Rzeki Czerwonej

Witold Zuchiewicz & Nguyen Quoc Cuong

Institute of Geological Sciences, Jagiellonian University, Oleandry 2A, 30-063 Kraków, Poland; E-mail: witold@ing.uj.edu.pl

Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Kraków, Senacka 1, 31-002 Kraków, Poland; E-mail: nqcuong_pl@yahoo.com



Abstract: *The Red River Fault Zone marks the boundary between the South China and Indochina blocks. It was shaped in two phases: during sinistral, ductile shear active 27-16 Ma, followed by exhumation and uplift from depths of 20-25 km, and then as dextral, predominantly brittle shear active in Plio-Quaternary times. The amount of post-Miocene dextral offset has been variously reconstructed as 20 to 57 km, whereas the size of individual offset of Quaternary valleys has been calculated as 9 m to nearly 2 km. Therefore, the corresponding rates of Quaternary dextral slip range between 1 and 9 mm/yr or 1 and 4 mm/yr. The fault zone is capable of generating relatively strong earthquakes in the future.*

Key words: *Red River Fault Zone, Vietnam, Plio-Quaternary*

Treść: *Strefa uskoku Rzeki Czerwonej wyznacza granicę pomiędzy blokami Chin południowych i Indochinami. Była ona ukształtowana w dwóch fazach: podczas lewoskrętnego ścinania w warunkach podatnych, w okresie 27 - 16 Ma z późniejszym wypiętrzeniem i ekshumacją z głębokości 20-25 km, a następnie w warunkach kruchego ścinania prawoskrętnego w plio-czwartorzędzie. Wielkość post-mioceńskiego przemieszczenia prawoskrętnego była rekonstruowana na 20 do 57 km, podczas gdy rozmiar przemieszczenia czwartorzędowych dolin był szacowany na 9 m do blisko 2 km. Dlatego ruch ten odpowiada tempu 1 do 9 mm/rok lub 1 do 4 mm/rok. Strefa uskokowa spełnia więc warunki umożliwiające w przyszłości generowanie silnych trzęsień ziemi.*

Słowa kluczowe: *strefa uskoku Rzeki Czerwonej, Wietnam, plio-czwartorzęd*

Introduction

The Red River Fault Zone (RRFZ) extending in the Yunnan province in China and in North Vietnam, and up to 20 km wide, is one of the main strike-slip fault zones in SE Asia that separates the South China and Indochina blocks (Fig. 1). Structural evolution of the RRFZ has been dealt with by a number of authors (cf. Tapponnier *et al*., 1990; Leloup *et al*., 1995; Cuong & Zuchiewicz, 2001; and references therein). The RRFZ is considered to have evolved in two phases: (1) an episode of sinistral ductile shear active between 27 and 16 Ma, followed by (2) a period of exhumation and uplift from depths of 20-25 km, accompanied by dextral, predominantly brittle shear active during the Plio-Quaternary (cf. Allen *et al*., 1984; Tapponnier *et al*., 1990; Lacassin *et al*., 1993; Leloup *et al*., 1995; and references therein). According to Jolivet *et al*. (2001), the RRFZ is rooted in an horizontal shear zone, at the brittle/ductile transition separating the upper and middle crust from the lower crust, and the sinistral strike-slip motion was first transpressional (?40 - 25 Ma), and then transtensional, leading to fast exhumation between 24 and 17 Ma. Wang *et al*. (1998) maintain that the sinistral shearing took place between 27 and

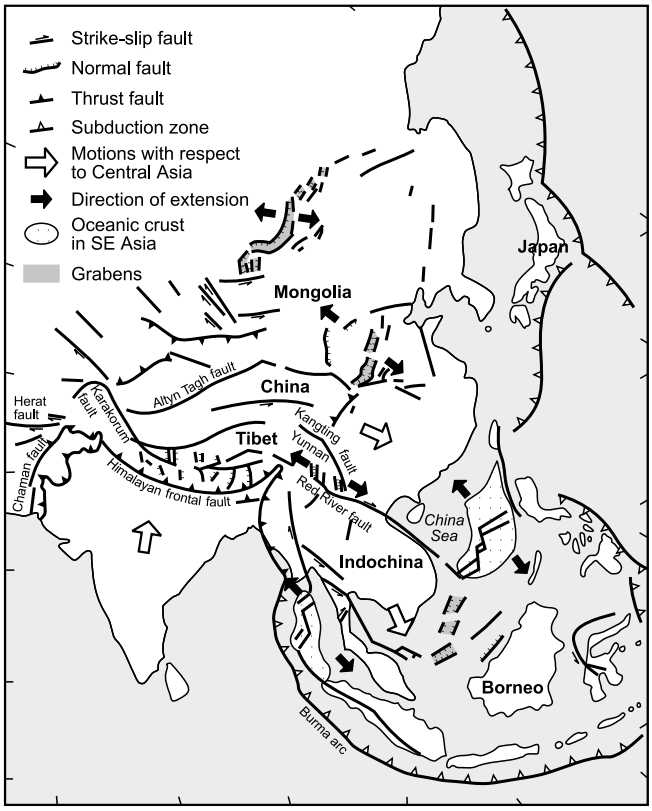


Fig. 1. Tectonic sketch of SE Asia (based on Tapponnier *et al*., 1990 and Huchon *et al*., 1994) • Szkic tektoniczny Azji południowo-wschodniej (w oparciu o Tapponnier *et al*., 1990 i Huchon *et al*., 1994)

17 Ma. However, recent fission-track studies indicate that the main period of ductile deformation in the RRFZ was completed by 25 Ma (Anczkiewicz *et al*., 2000) or 26 Ma (Żelaźniewicz *et al*., 2005) and new structural and geochronological data appear to document the polyphase, ductile shear active between the Early Cretaceous and the Miocene, which included dextral, sinistral and dextral transpression, and sinistral transtension regimes (Żelaźniewicz *et al*., 2005). The Late Miocene change of the sense of motion is commonly related to the history of collision between India and Eurasia (Tapponnier *et al*., 1990; Schaerer *et al*., 1994; Harrison *et al*., 1995).

The RRFZ represents a strike-slip zone showing transpression in the NW and transtension in the SE parts (Leloup *et al*., 1995). As compared to the recently dextral Red River (*Song Hong*) fault zone (RRFZ), the Dien Bien Phu Fault Zone (DBP) is a sinistral, probably conjugate fault (cf. Trinh *et al*., 1999; Hung & Vinh 2001; Zuchiewicz *et al*., 2002; cf. also Figs 2-4). Both the RRFZ and DBP are very important strike-slip fault zones of SE Asia, whose Quaternary structural history has not been fully recognised.

In North Vietnam, the RRFZ is subdivided into three principal branches, up to 300 km long, trending roughly NW-SE and named from NE to SW: the Lo River, the Chay River, and the Red River faults (Figs 5, 6). These are mostly dextral and dextral-normal faults that show the southeastwards-increasing component of normal slip (Trinh, 1995). Between the Lo and the Chay River faults recently growing, WNW-ESE- and W-E-trending anticlines, have been found (Lacassin *et al*., 1994).

Seismicity

Neither in Yunnan Province nor in the North Vietnamese segment of the RRFZ, earthquakes of M>5.5 have been recorded (Fig. 6; cf. also Allen *et al*., 1984; Lap, 1989, 1991). This may point to either a long recurrence interval of strong earthquakes in this zone (Allen *et al*., 1984) and present-day locking of the fault at depths of 5-20 km (Cong & Feigl, 1999), or the predominance of fault creep mechanism in the Pliocene-Quaternary period (Cuong *et al*., 1999).

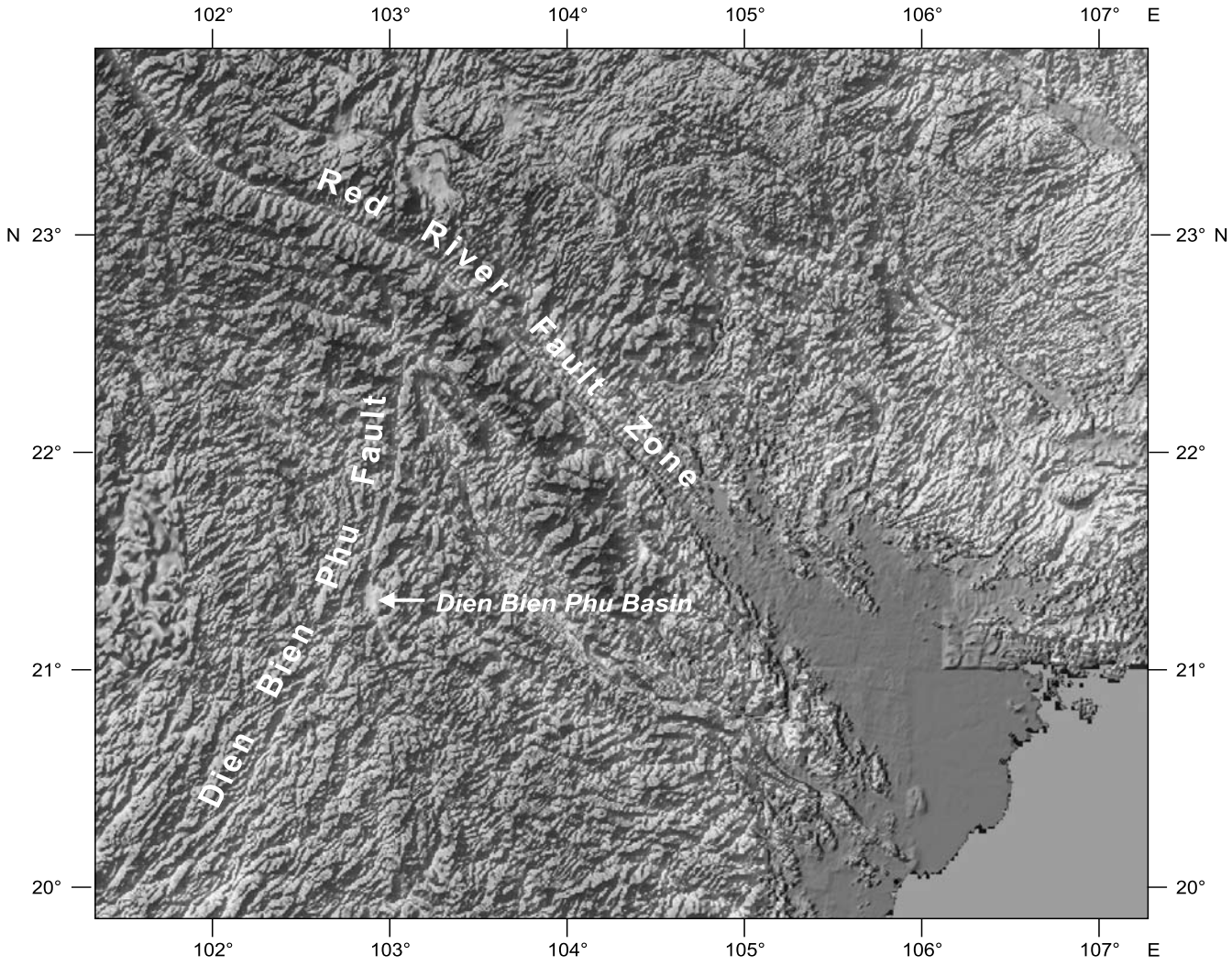


Fig. 2. Digital elevation model of the Red River and the Dien Bien Phu fault zones in Northern Vietnam (SRTM image based on data provided by USGS) • Numeryczny model terenu stref uskokowych Rzeki Czerwonej i Dien Bien Phu w północnym Wietnamie (obraz SRTM w oparciu o dane USGS)

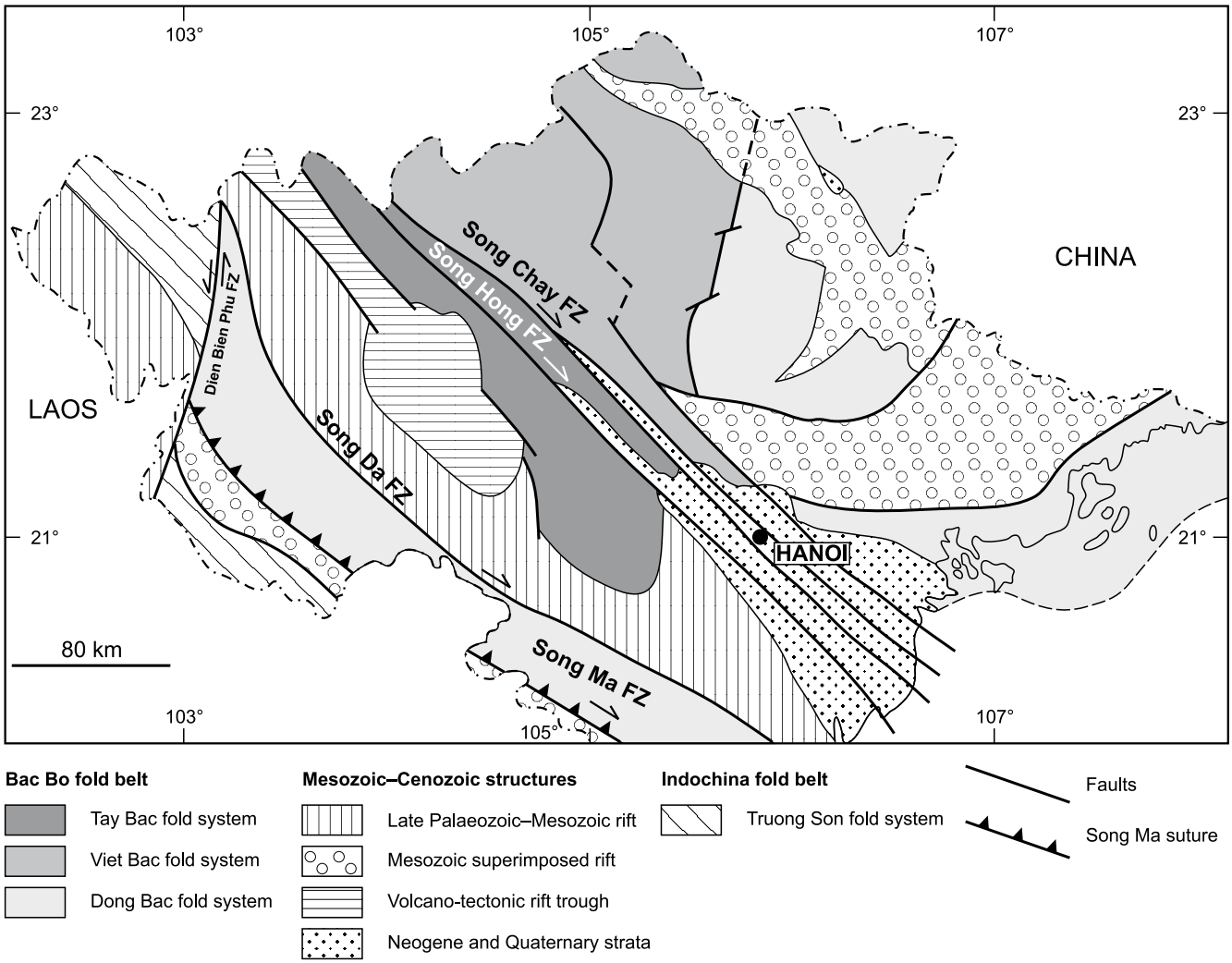


Fig. 3. Simplified geological map of Northern Vietnam (based on Tri *et al*., 1979; modified) • Uproszczona mapa geologiczna północnego Wietnamu (w oparciu o Tri *et al*., 1979, zmodyfikowane)

Amplitudes and rates of slip in the light of previous studies

The amount of sinistral offset along the RRFZ has been estimated at 330±60 km (Lacassin *et al*., 1993) to 500-700 km (Tapponnier *et al*., 1990; Leloup *et al*., 1995), that of post-Miocene dextral offset being variably reconstructed at 20-57 km (Allen *et al*., 1984), 37 km (Tuc & Yem, 2001) or even 200-250 km (Leloup *et al*., 1995). The size of individual offset of Quaternary valleys has been calculated, depending on their size, as: 9 m to 6 km, and even 20 km (Allen *et al*., 1984), 70 m to 17 km (Tuc & Yem, 2001), 200-1200 m (Trinh *et al*., 1993; Trinh, 1995), 0.3-2 km (Lacassin *et al*., 1994) or up to 2 km (Cuong & Zuchiewicz, 2001). Therefore, the corresponding rates of Quaternary dextral slip range between 1 and 9 mm/yr (Allen *et al*., 1984) or 1 and 4 mm/yr (Weldon *et al*., 1994) whereas geodetically measured rates of recent motions do not exceed 4 mm/yr (Cong & Feigl, 1999; To *et al*., 1999) or 2 mm/yr (To *et al*., 2001). The rates of recent uplift fall into 0.1-1 mm/yr interval (cf. Allen *et al*., 1984; Trinh *et al*., 1993; Tuc & Yem, 2001; Cuong & Zuchiewicz, 2001).

As far as long-term uplift rates are concerned, the size of erosional dissection can be used as one of proxy methods. The amount of post-Miocene unroofing in the RRFZ can be estimated at 800 m in the Yunnan Province (Allen *et al*., 1984), to 950-1,240 m, 500-1,000 m, and 300 m in the upper, *middle***,** and lower SE reaches, respectively (Zuchiewicz & Cuong, 2003; Zuchiewicz *et al*., 2004). The onset of fluvial incision is difficult to constrain; it probably coincides with the Early Pliocene when vigorous uplift of the Tibetan Plateau has commenced (e.g., Allen *et al*., 1984). Hence, the maximum long-term uplift rates along the RRFZ can be roughly calculated as 0.06 to 0.24 mm/yr. The highest figures are confined to the NW portion of the RRFZ (Zuchiewicz & Cuong, 2003; Zuchiewicz *et al*., 2004). An *et al*. (2000) estimate the size of young uplift (without any age constraints, however) at 275 to 550 m, and cite the average uplift rates ranging between 0.14 and 0.28 mm/yr. Data gathered in the Phan Si Pan granites, occurring SW of the Red River Fault in the NW part of the zone, point to 4-7 km of uplift since the beginning of the Pliocene, what gives average uplift rates between 0.8 and 1.4 mm/yr (Trinh *et al*., 1999).

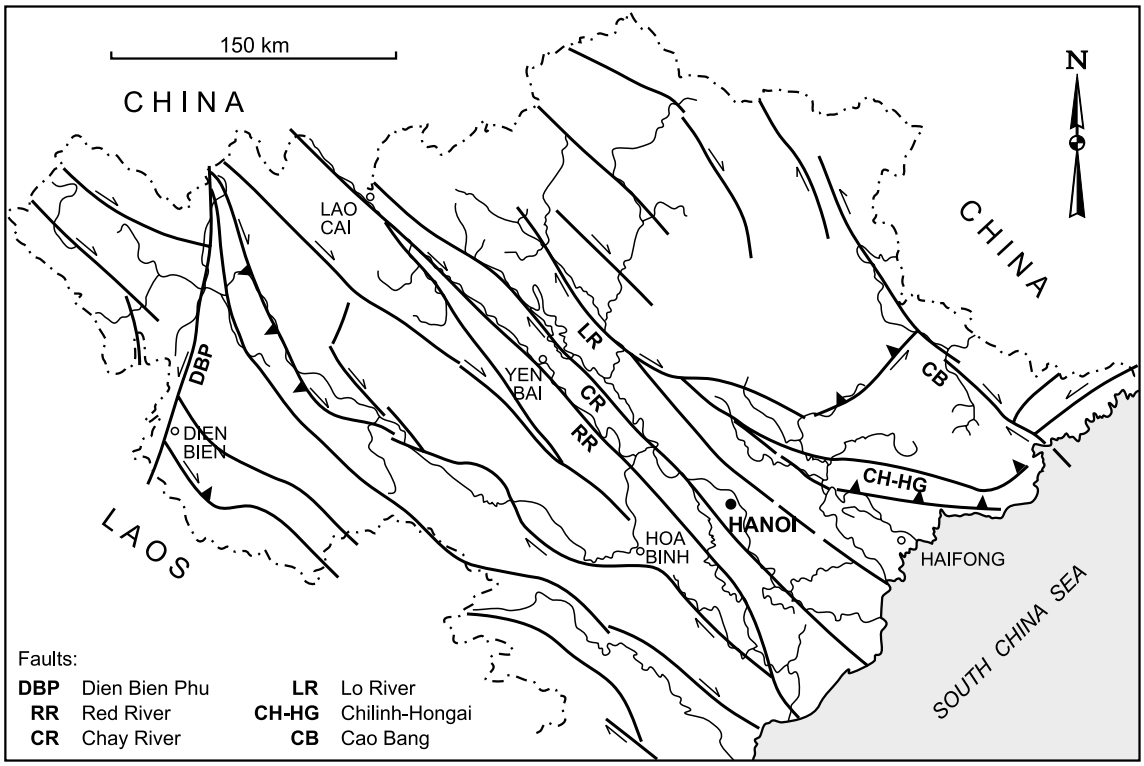


Fig. 4. Pattern of young faults in NW Vietnam • Młode uskoki w północno-zachodnim Wietnamie

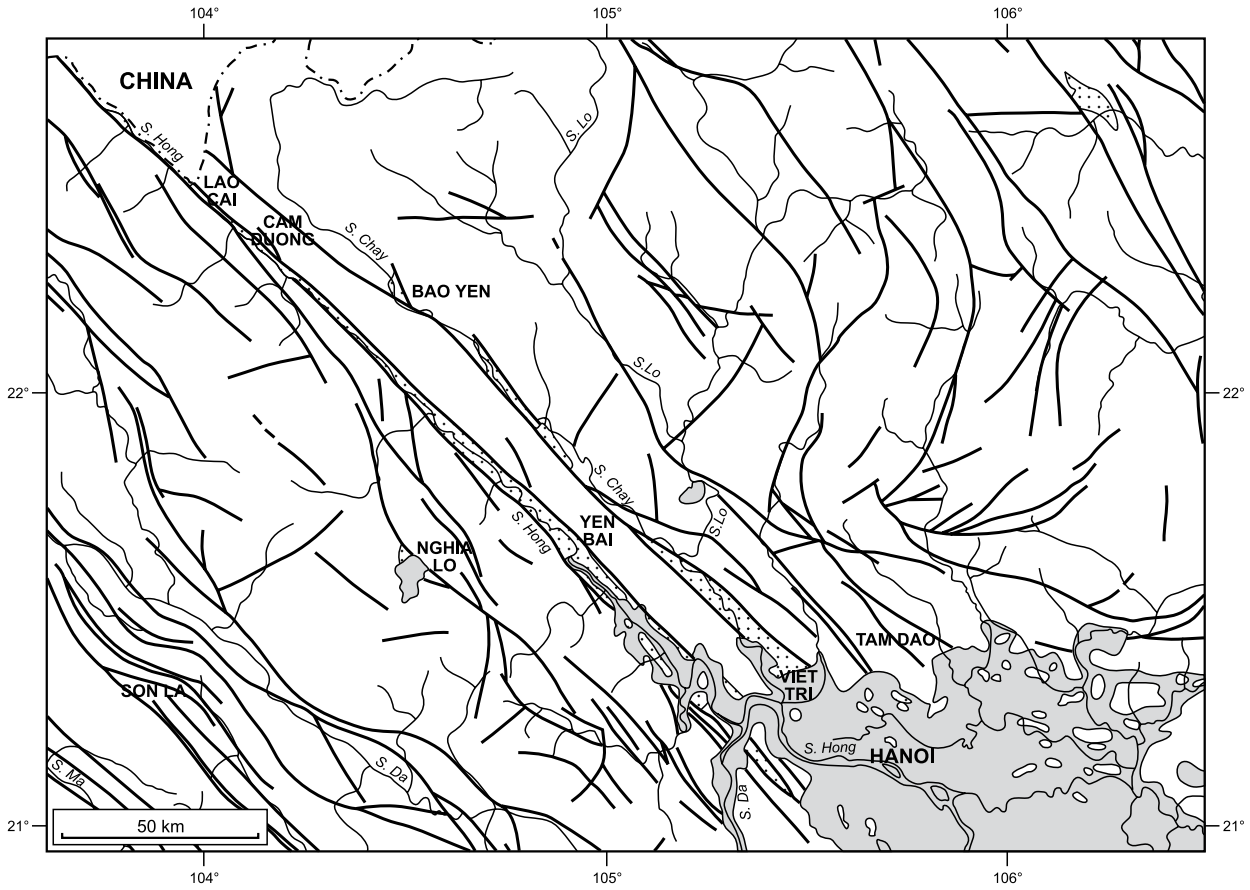


Fig. 5. Simplified tectonic sketch map of the Red River Fault Zone in Vietnam (based on Tri *et al*., 1973). Exposures of terrestrial, lower through middle Neogene strata are dotted, shaded areas denote Quaternary sediments • Uproszczony szkic tektoniczny strefy uskoku Rzeki Czerwonej w Wietnamie (w oparciu o Tri *et al*., 1973). Odsłonięcia utworów lądowych dolnego i środkowego neogenu są wykropkowane, na szaro zaznaczone są osady czwartorzędowe

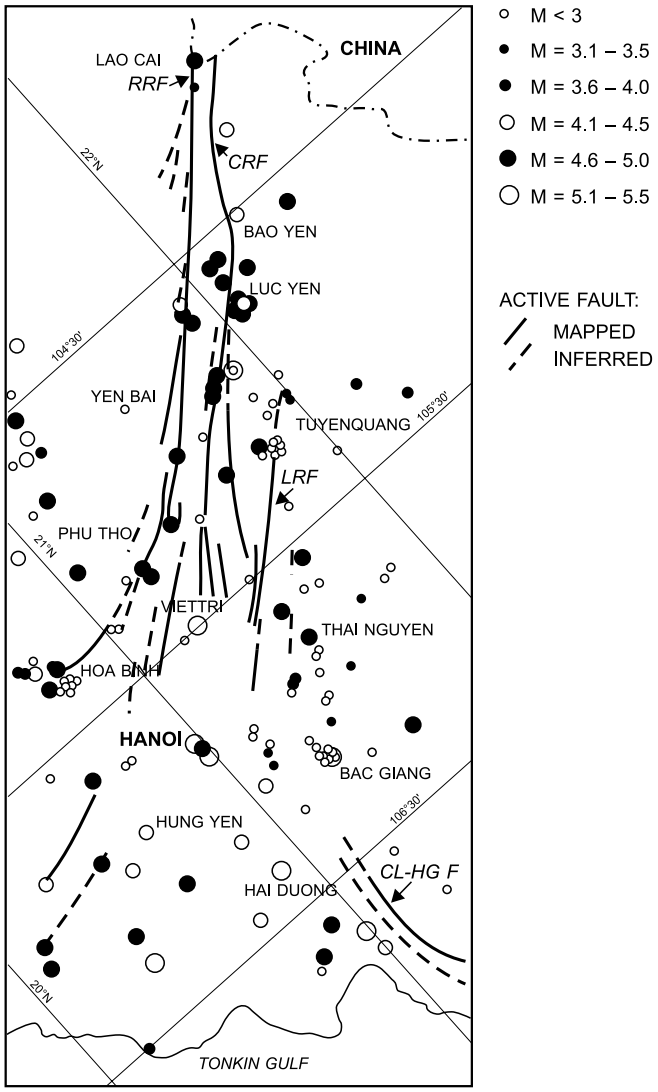


Fig. 6. Pattern of historic seismicity in the RRFZ in northern Vietnam. RRF - Red River Fault, CRF - Chay River Fault, LRF - Lo River Fault, CL-HG F - Chi Linh-Hon Gai Fault • Historyczna sejsmiczność w strefie uskoku Rzeki Czerwonej w północnym Wietnamie. RRF – uskok Rzeki Czerwonej, CRF – uskok Rzeki Chay, uskok Rzeki Lo, CL-HGF – uskok Chi Linh – Hon Gai

Geomorphic features and Quaternary sediments in the Red River valley: Yen Bai test area

According to Makarov *et al*. (1988), the oldest fragments of *planation surfaces* preserved at the parallel of Nghia Lo and Yen Bai, and farther south (Fig. 7) are of Middle or Late Miocene ages whereas on the limbs of the uplifted area Pliocene and Quaternary planation surfaces are believed to occur. However, the main episode of planation in that part of Vietnam has been attributed by An (1981) to the Late Miocene-Early Pliocene. An et al. (2000 distinguished three topographic levels on either side of the Red River valley, of elevations increasing from the NW to SE: 400-200 m a.s.l., 600-300 (200) m a.s.l., and 1,200 (800) - 400 m a.s.l.; the last one being the highest on the NE side of the fault zone. The two higher levels are tilted southeastwards at 0.75 to 2%. Unfortunately, these authors do not provide any hints as to the age of these "levels".

Vinh *et al*. (1978) have distinguished two *terraces* of Early and Middle Pleistocene age (30-35 m, 20-25 m) in the Red River valley near Yen Bai, whose alluvial covers composed of 2-11-m-thick polymictic gravels and pebbles rest on straths, as well as one Late Pleistocene terrace (10-15 m) composed of 10-18-m-thick polymictic gravels built up of volcanic and magmatic rocks along with sandstones and quartzites. Holocene sediments are represented by 7-8-m-thick gravels and sands of bedload facies, fine-grained sands and clays of overbank facies, as well as 1-2-m-thick mire deposits, composed of black, organic clays and peat. Tri *et al*. (1979), in turn, have distinguished in the Red River valley a flight of more than 10 terrace steps of relative altitudes up to 65-75 m.

Fluvial terraces of the Red River valley near Yen Bai are deformed, as shown by Makarov *et al*. (1988). On the right bank of the river, at The Phuang, the 12-m-high strath of the 20-m-tall terrace (Q_3^1) has been tilted eastwards at 7°. The author's observations indicate that the strath is comprises Neogene paraconglomerates, mudstones and siltstones dipping to SW (210/56) and cut by a reverse fault of attitude changing from 50/41 to 35/60. The fault must have been reactivated during a subsequent episode of deformation as a normal fault. According to Makarov *et al*. (1988), the relative height of the Q_3^1 terrace north of Yen Bai rises abnormally to some 50 m.

Shortly west of Yen Bai, a young sedimentary basin of Nghia Lo occurs, originated in the early Cenozoic (Vinh *et al*., 1978) and intensively developing in the Pliocene through the beginning of the Middle Pleistocene (Makarov *et al*., 1988). Quaternary infill of this basin (Vinh *et al*., 1978) is represented by terrace IV (25-30 m; Early-Middle Pleistocene), III (more than 30-35-m-thick alluvium of Middle and Late Pleistocene age), and II (10-15-m-thick alluvium of Late Pleistocene age) sediments, as well as by Early-Middle Holocene alluvium, up to 26 m thick. These strata are dominated by coarse-clastic material composed of clasts from 8-10 cm up to 20-30 cm in diameter, the Lower and Middle Pleistocene sediments containing also large boulders. Silty and clayey intercalations are up to 1-2 m thick; being mostly composed of kaolinite (80-90%), rarely hydromicas, haemathite, and hydrohaematite.

Field studies conducted in the Red River valley between Trai Hut in the NW and Yen Bai in the SE enabled for identification of three cut-and-fill (2-3 m, 4-6 m, 8 m) and four to five strath (11-13 m, 15-16 m, 20 m, 30 m, 40-50 m) terraces. The thickness of gravel covers usually attains 2-3 m, rarely 5-7 m. Overbank sediments are the thickest within the 8-9 m terrace. All these terraces are dextrally offset together with corresponding alluvial fans of tributary valleys.

Morphotectonic setting

Morphotectonic features of the RRFZ in Yunnan Province have been dealt with extensively by Allen *et al*. (1984) and later by Weldon *et al*. (1994), whereas for the Vietnamese segment of this zone only a few reviews and preliminary reports are available (i.a., Trinh *et al*., 1993; Winter & Costaz, 1993; Lacassin *et al*., 1994; Trinh, 1995; Cuong *et al*., 1999; Cuong & Zuchiewicz, 2001).

Indicators of the right-lateral slip, particularly well-visible along some traces of the Chay River (north of Yen Bai) and the Red River fault (south of Lao Cai, Cam Duong, Trai Hut) segments, are: drainage deflection (from 10-50 m to 2,500 m), beheaded streams, shutter ridges, *en echelon*-oriented minor fault and fault-line scarps, displaced terraces and alluvial fans, rectilinear fault valleys, and long rectilinear fault scarps of relief not exceeding 30-50 m (Cuong *et al*., 1999).

The amounts of right-lateral offset deduced from deflected drainage pattern, obtained for 8-10 km to 20-25-km-long fault segments, range from 500 to 3,000 m; the cumulative offset amounting to 4 -10 km and varying in individual RRFZ branches (Figs 7, 8).

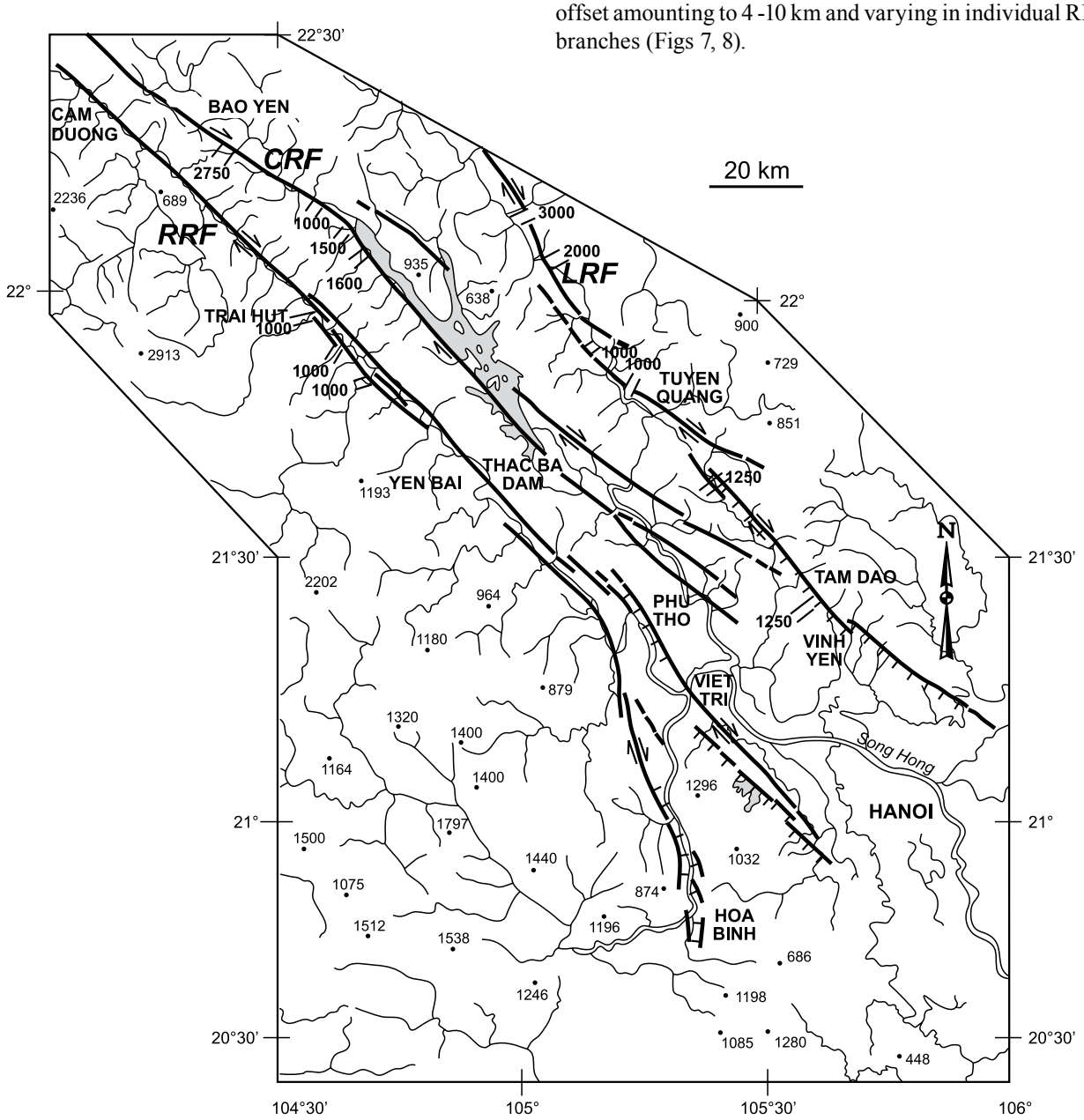


Fig. 7. Young faults in the Vietnamese segment of the RRFZ (based on Trinh, 1995; modified). Sense of strike-slip motion is arrowed, barbed lines denote normal faults, bold numbers on the fault traces indicate recent offset (in metres) estimated from drainage deflection; the other numbers show elevation in metres a.s.l. RRFZ fault branches: RRF - Red River Fault, CRF - Chay River Fault, LRF - Lo River Fault • Młode uskoki w wietnamskim segmencie strefy uskoku Rzeki Czerwonej (w oparciu o Trinh, 1995, zmodyfikowane). Zwroty przemieszczenia przesuwczego zaznaczone strzałkami, linie ząbkowane oznaczają uskoki normalne, litery wytłuszczone przy uskokach wskazują współczesne przemieszczenie (w metrach) oszacowane w oparciu o defleksję sieci drenażu, pozostałe symbole oznaczają wysokości w metrach nad poziom morza. Odgałęzienia strefy uskoku Rzeki Czerwonej: RRF – uskok Rzeki Czerwonej, CRF – uskok Rzeki Chay, LRF – uskok Rzeki Lo

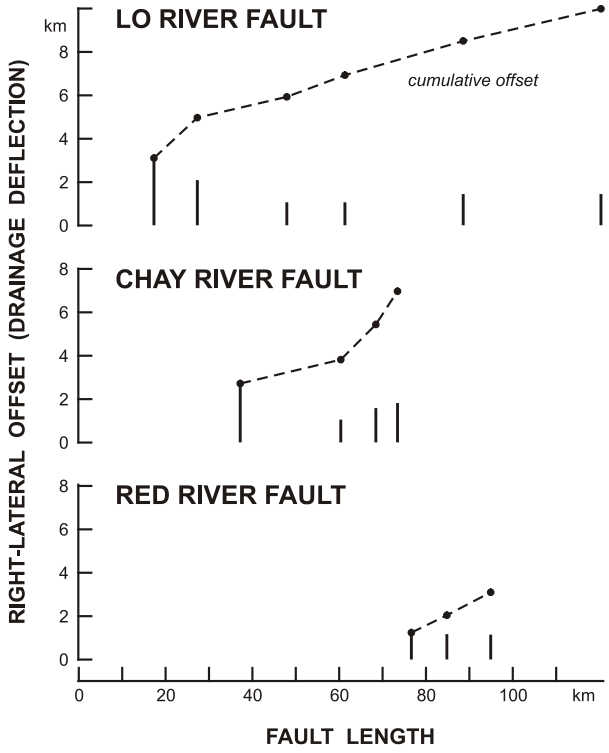


Fig. 8. Amount of Recent dextral offset along main branches of the RRFZ, calculated for the segment shown in Fig. 7 • Wielkość współczesnego prawoprzesuwczego przemieszczenia wzdłuż głównych odgałęzień strefy uskokowej Rzeki Czerwonej, obliczone dla segmentu wskazanego na figurze 7

Morphotectonic *indicators of predominantly normal slip* in the SE segments of the Red River, Chay River and Lo River fault branches include: well-developed triangular facets, ubiquitous occurrence of hanging wine-glass (hour-glass) valleys and rectilinear fault scarps at the feet of mountain fronts, frequently accompanied by associated half-grabens and minor horsts or pressure-ridges (Cuong *et al*., 1999). The most spectacular example of such features is provided by a fragment of the Lo River fault near Tam Dao (Zuchiewicz & Cuong, 2001).

Conclusions

Geomorphic signatures observed along the Red River Fault Zone in Vietnam, combined with the results of recent geodetic studies, point to relatively strong seismic potential of the zone, particularly in its SE segment.

Streszczenie

Młode uskoki w północnym Wietnamie: przykład ze strefy uskoku Rzeki Czerwonej

Strefa uskoku Rzeki Czerwonej (SURC) w prowincji Junan (Chiny) i północnym Wietnamie jest jednym z głównych uskoków przesuwczych Azji SE, który rozdziela bloki południowochiński oraz Indochin. Dotychczasowe badania sugerują, że uskok ten reprezentuje wielkoskalową strefę ścinania, powstałą w trakcie dwóch faz: (1) podczas lewoskrętnego ścinania w warunkach podatnych w okresie 27-16 Ma (z kulminacją 21-16 Ma, zastąpionego przez wypiętrzenie i ekshumację skał skorupy z głębokości ok. 20-25 km), a następnie (2) w warunkach kruchego ścinania prawoskrętnego, począwszy od ok. 5,5 Ma. Skalę przemieszczenia lewoskrętnego oceniano na 550-900 km, a rozmiary młodszego przemieszczenia prawoskrętnego - od kilku metrów do 5,5 km, a nawet 20-30 km.

Zarówno w prowincji Junan, jak też w północnowietnamskim segmencie SURC nie zanotowano wstrząsów sejmicznych o magnitudzie przekraczającej 5,9 w skali Richtera. Może to sugerować bardzo długotrwały interwał powtarzalności silnych wstrzasów, względnie wskazywać na przewagę mechanizmu pełznięcia uskokowego w pliocenie i czwartorzędzie.

SURC w północnym Wietnamie dzieli się na trzy odnogi o orientacji NW-SE i długości ok. 300 km zwane, od NE ku SW, uskokami rzek: Lo, Chay i Czerwonej. Są to uskoki prawo- i prawo-normalnoprzesuwcze, wykazujące wzrastającą ku SE rolę składowej normalnej.

Celem naszych badań był przegląd wszystkich dostępnych dowodów na prawo-normalnoprzesuwczy charakter przemieszczenia wzdłuż wymienionych stref uskokowych w pliocenie i czwartorzędzie. Badania terenowe polegały na analizie morfostrukturalnej i strukturalnej osadów górnokenozoicznych, jak również na fotointerpretacji dostępnych zdjęć lotniczych i satelitarnych oraz analizie map topograficznych w skali 1:50 000 i 1:10 000.

Do wskaźników morfotektonicznych przemieszczenia normalnego wzdłuż SE segmentów uskoków rzek Czerwonej, Lo i Chay należą: dobrze rozwinięte trójkątne lica progów uskokowych, liczne doliny zawieszone typu dolin butelkowych, a także prostolinijne skarpy uskokowe u podnóża masywów górskich, którym towarzyszą półrowy tektoniczne i drobne zręby, względnie grzbiety typu *pressure ridges*. Najbardziej spektakularnych przykładów dostarcza segment uskoku Rzeki Lo w rejonie Tam Dao.

Wskaźniki ruchu prawoprzesuwczego, szczególnie dobrze widoczne wzdłuż segmentów uskoków Rzek Chay oraz Czerwonej, obejmują: prawoskrętną defleksję sieci drenażu (1-50 m do 2500 m), potoki pozbawione odcinków źródłowych, grzbiety zagradzające, kulisowo ułożone drobne skarpy uskokowe i pseudouskokowe, zdyslokowane terasy rzeczne i stożki napływowe, prostilinijne doliny uskokowe oraz długie, prostolinijne skarpy uskokowe o wysokości względnej nie przekraczającej 30-50 m.

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